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Measurement of the hot spot electron temperature in NIF ICF implosions using Krypton x-ray emission spectroscopy

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Measurement of the hot spot electron temperature in NIF ICF implosions using Krypton x-ray emission spectroscopy

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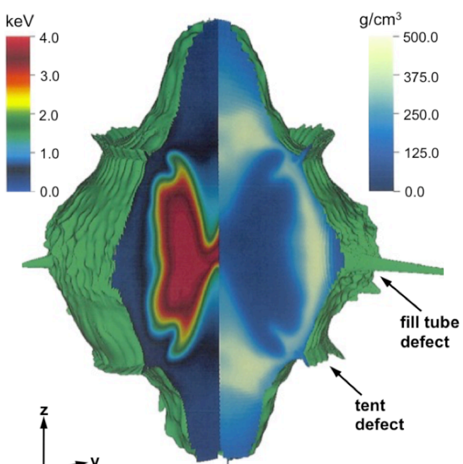
We are developing expertise in x-ray spectroscopy of ICF implosions with a near-term focus of measuring Te's

- The inference of ion temperature from neutron spectral measurements in indirect-drive ICF is known to be sensitive to non-thermal velocity distributions in the fuel.
- The electron temperature (Te) inferred from dopant line ratios should not be sensitive to these bulk motions and hence may be a better measure of the thermal temperature of the hot spot.
- The initial Krypton-doped, gas-filled symcap experiment produced a measurable Krypton spectrum, and encouraging implosion performance.

The electron temperature describes the heating achieved in an ICF implosion

3D simulation of a high-foot implosion at stagnation



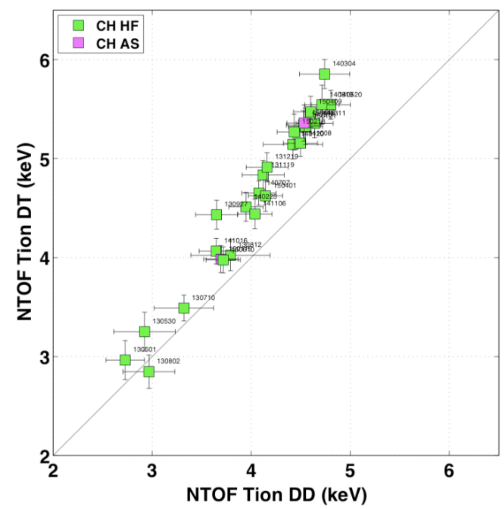
D. Clark, 3D HYDRA

The perturbed hot spot of a typical implosion exhibits:

- hot spot flow
- anisotropic velocities
- bulk motion

that can result in apparent T_{ion} differences along different line-of-sights

Measured DT vs. DD ion temperatures diverge



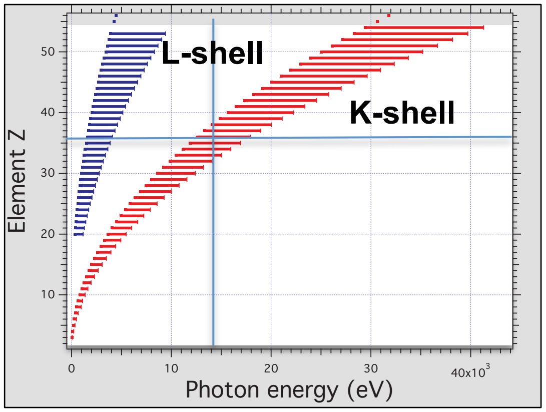
Across the ensemble of DT layered experiments completed on the NIF, there is a discrepancy between the measured DD and DT T_{ion}

Electron temperature (Te) inferred from spectroscopic line ratios should not be sensitive to these bulk motions

The addition of a dopant to a capsule fuel gas must be chosen to satisfy competing constraints

Why Krypton?

- To dope a capsule fill gas uniformly, we must use a gas
- The dopant element must have line emission that can escape the high areal density shell with minimal attenuation



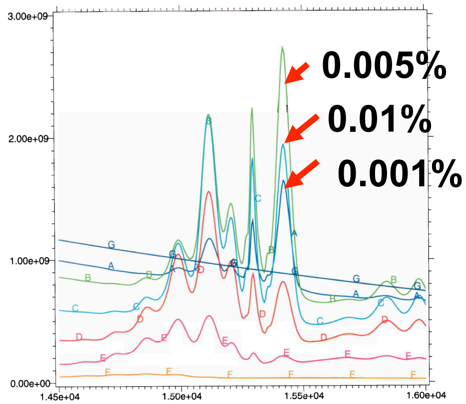
Kr lines	Energy
Kr He-α	13.1 keV
Kr He-β	15.4 keV
Kr Ly-α	13.5 keV
Kr Ly-β	15.9 keV
Kr He-γ	16.2 keV

Krypton (Z=36) fulfills these requirements

Selecting a Kr dopant fraction

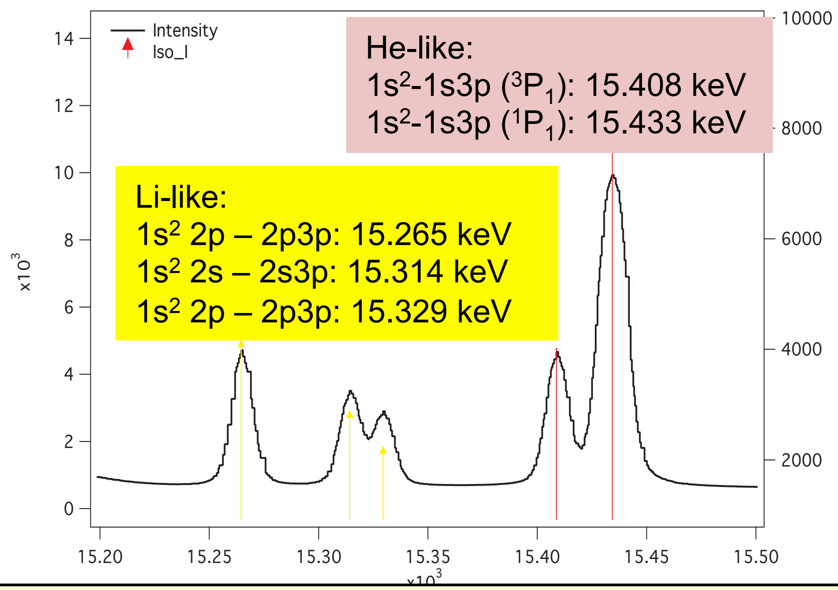
- High enough that we can get enough photons out
- But minimally perturb the hot spot dynamics (e.g., due to radiative cooling, kinetic effects)
- Minimal opacity of the lines we're interested in

Cretin simulations of signal variation with dopant level



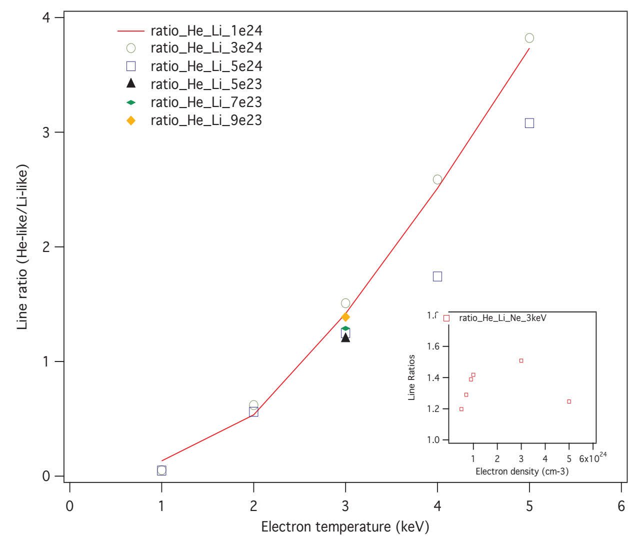
The He-like to Li-like line ratio is sensitive to Te

Lines must escape the compressed shell



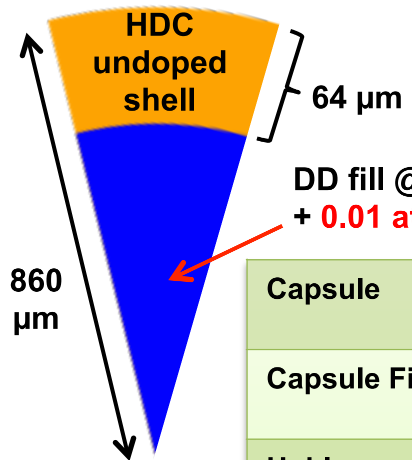
Krypton Li-like and He-like (He-β) lines occur at >15 keV – where emission can escape the shell

The ratio of lines must show sensitivity over range of implosion temperatures



He-like / Li-like ratio increases 5x over a Te change from 2 - 4 keV

0.01at% Krypton dopant was added to the DD fill of an integrated symcap implosion

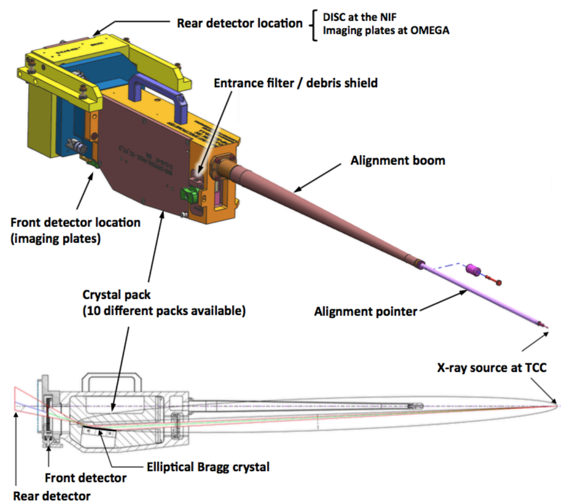


DD fill @ 4.5 mg/cc
+ 0.01 at% Krypton

Platform:

Capsule	“subscale” undoped HDC
Capsule Fill	4.5 mg/cc DD + 0.01at% Kr
Hohlraum	Au, 5.75 mm diameter, 10.1 mm length
Hohlraum Fill	0.03 mg/cc 4He
Laser Drive	3 shock pulse, 0.9 MJ, 300 TW
Fielding Temp	78 K

NXS Spectrometer:

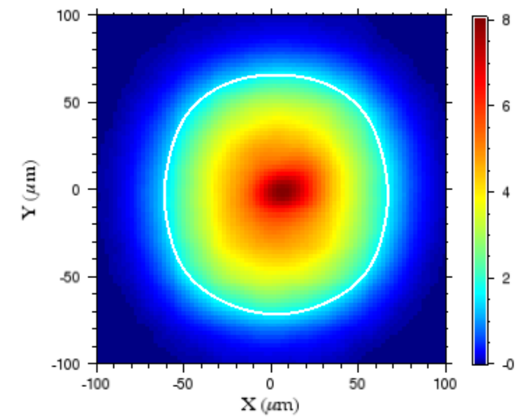


Crystal	Singly-Curved Elliptical Bragg Crystal 10 (highest energy)
Spectral Coverage	10.8 – 18.2 keV
Resolving Power	E/ΔE ≥ 50
Detector	Image Plate, over 3 filtration windows
DIM	00-00

Implosion performance minimally perturbed by the 0.01at% Krypton dopant

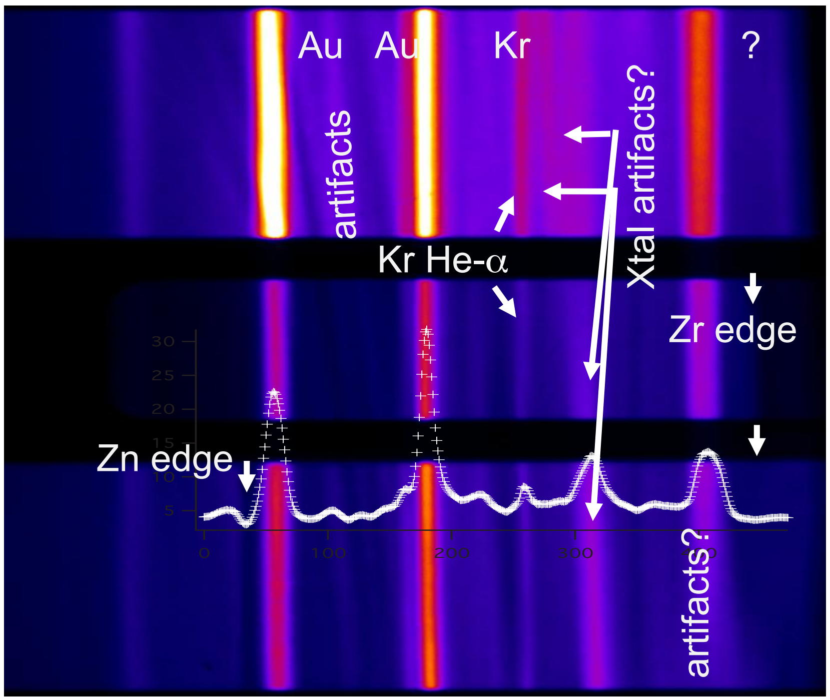
	N150812-001 DD w/ 0.01at% Kr @ 4.5 mg/cc	1D simulation	
		Clean	0.01at% Kr
DD Yield	7.8 ± 0.8 e12 (DD w/ Kr)	**9.0e12**	**7.1e12**
DD T_i (keV)	2.8 ± 0.3	**2.53***	**2.46***
X-ray BT (ns)	8.28 ± 0.03	**8.48**	**8.45**
X-ray burn (ps)	296 ± 70	**273**	**286**

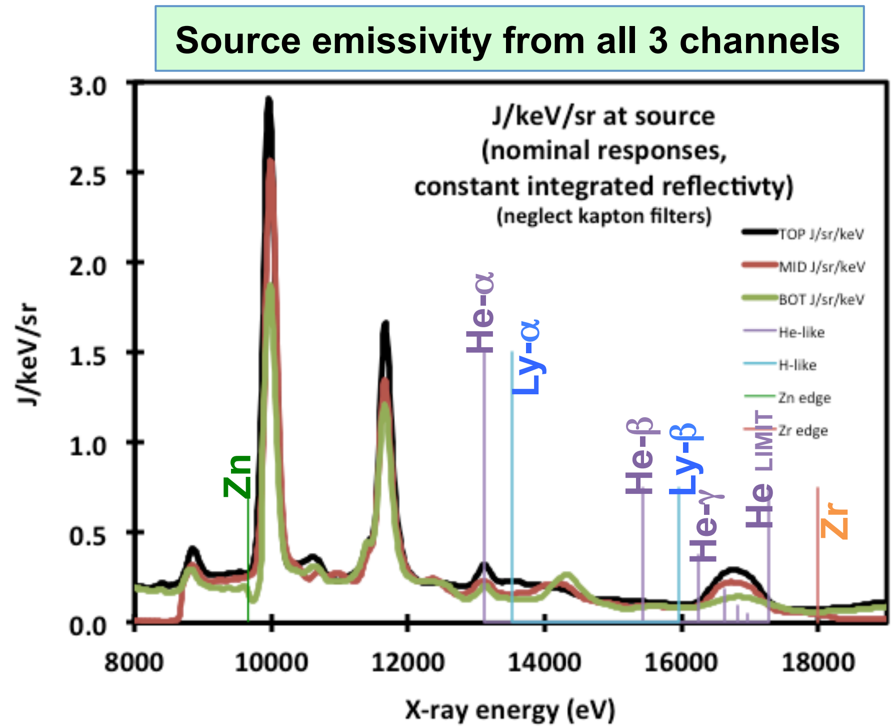
Time-integrated hot spot emission, viewed from equator line-of-sight



P0 = 66.2 ± 1.0 μm
P2/P0 = 6.2 ± 0.8 %
P4/P0 = -3.4 ± 0.4 %

Krypton spectra from NXS showed He-α, but no Li-like lines; strong contribution from Au hohlraum plasma





*assuming a uniform 0.94 mrad reflectivity for the crystal

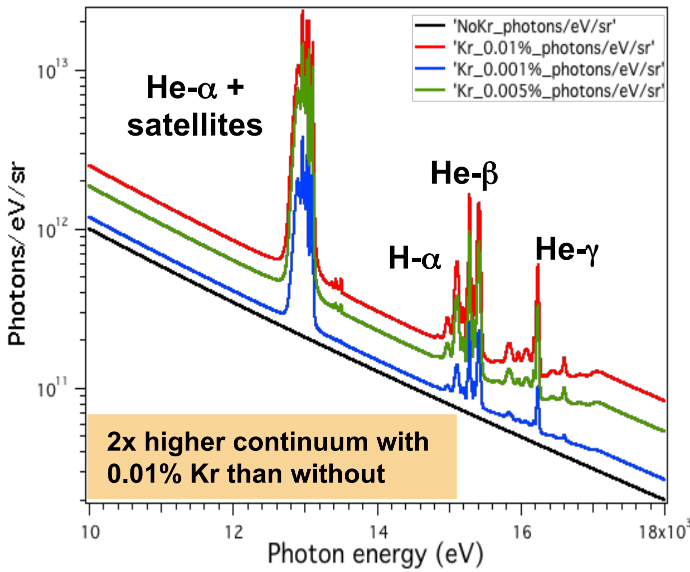
Post-shot 1D capsule simulations are post-processed using Cretin atomic code to generate spectra

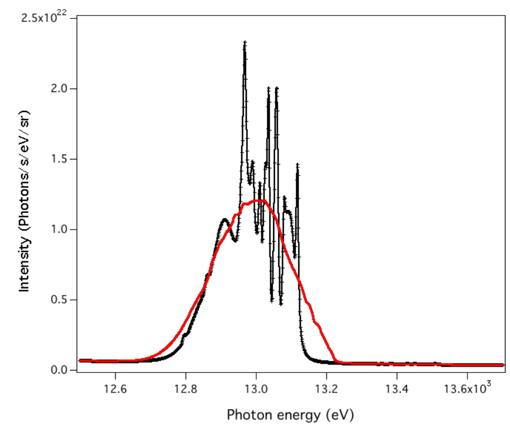
Post-shot Cretin calculation used the data from 1D HYDRA capsule simulation for time steps of ~50 ps. It includes:

- **Kr data of DCA-36k,**
- **Hydrogenic atomic data for H, He and C**
- **Time dependent kinetics**
- **Continuum radiation transfer**
- **Stark broadening**
- **Optical depth**

The data is then post processed with NXS response to be comparable to the experimental data.

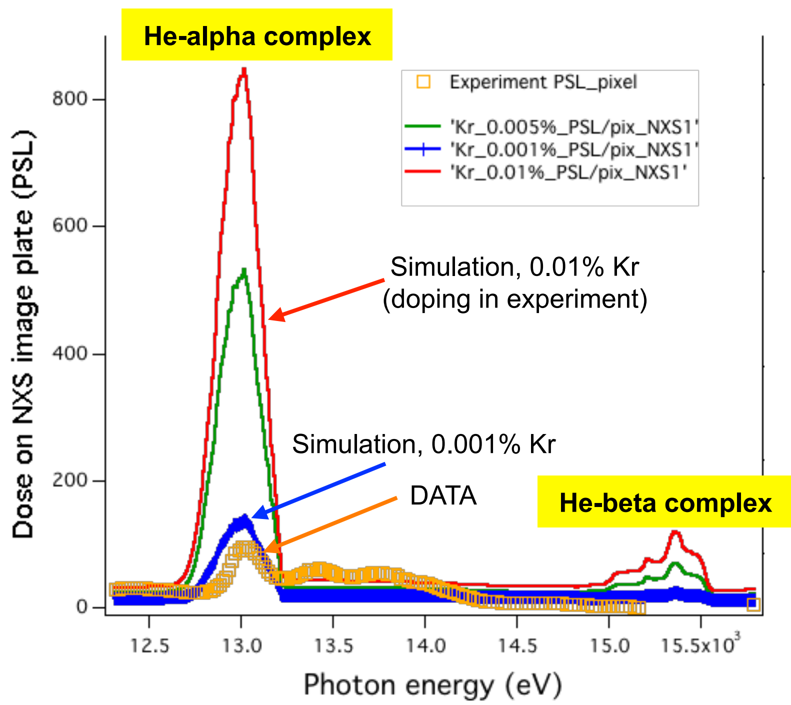
Cretin calculations try to match both absolute continuum level and lineshapes





Calculated spectrum folding in spectral resolving power of the detector (E/ΔE=60)

Measured line emission for Kr He-α is fit by 1/10th the expected dopant fraction



- Cretin data based on 1D Hydra simulations show:
  - Higher expected spectral signal relative to measurement
  - The charge states are dominated by Be-, Li-, and He-like ions
- Work in progress:
  - 2D Hydra model and Cretin spectral analysis
  - Estimate upper bound Te from the spectral lines

The results of the shot will drive improvements to future platform fielding

1. Increase Kr doping to strengthen emission without compromising performance
2. Increase the implosion temperature to optimize charge balance and He-β emission
3. Time-gate the detector to reduce unwanted Au emission
4. Replace crystal to remove spectrometer artifacts
5. Work toward space- and time-resolved data
6. Simultaneously obtain continuum emission measurement for Te

We are developing spectroscopic techniques to measure the electron temperature of ICF plasmas

- Trace levels of Krypton were added to the capsule fill gas of a surrogate ignition capsule (Symcap) to directly diagnose the hot spot using spectroscopy
- The initial experiment of this campaign could only identify the Kr He-α line
- However, the low dopant fraction minimally perturbed the implosion, leaving room to increase the dopant fraction in subsequent experiments
- Work is in progress to improve modeling and spectral analysis
- Spectroscopy will ultimately serve as a valuable Te measurement for select implosions to accompany the continuum measurements of Te

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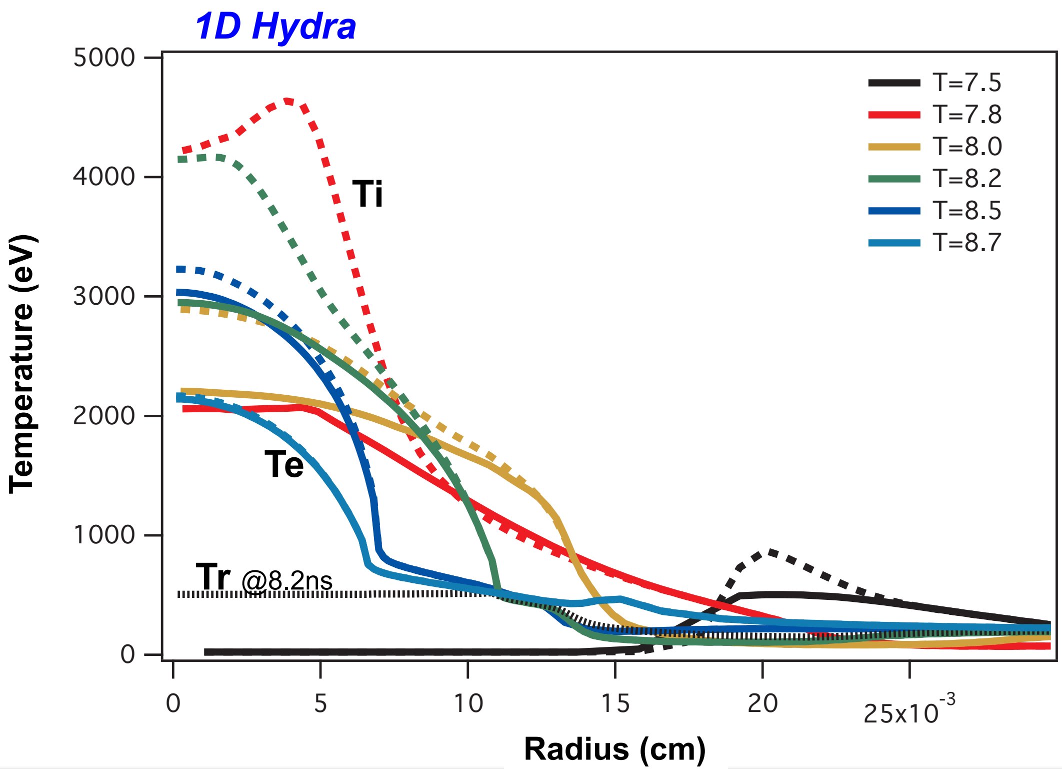
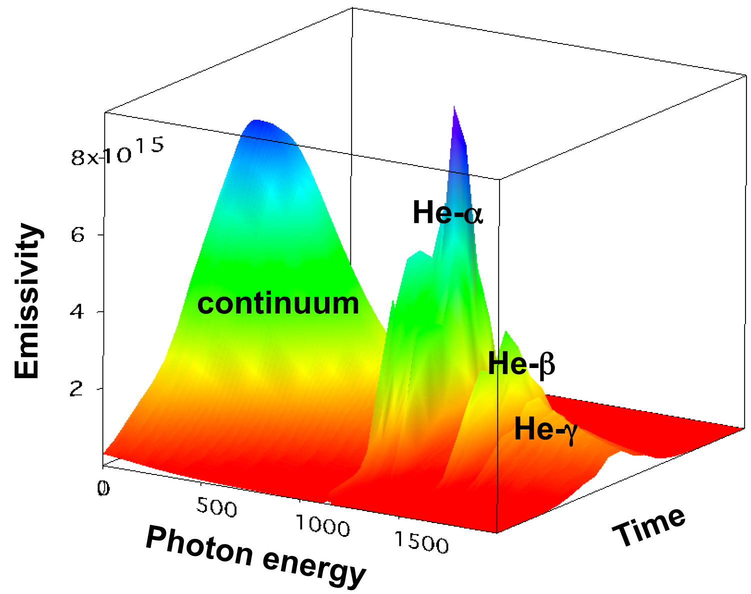
The Krypton spectrum is very time-dependent due to rapidly evolving temperatures and densities





The initial measurement will integrate over time and space